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Scenarios and prospects of solid biofuel use in Brazil

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ABSTRACT

Sustainability is a major goal for the country development without negative effects on climate change, allied to scarcity and instability in the fossil fuels prices, makes attractive the use of several agricultural, forestry and industrial biomass which may undergo combustion processes for the production of renewable energy, either in its in natural form, pressed into dense pellets or briquettes, or after thermochemical conversion through gasification, pyrolysis, liquefaction, carbonization, and torrefaction. The aim of the current research was to identify the major environmental, economic and social impacts arising from the solid fossil fuels, as well as introduce a technical approach to address the scenario of the main energy crops produced in Brazil, wastes arising from the same, their quantification, and alternatives to using such wastes in the solid biofuels production. Moreover, it was intended to describe the current national and global market, policies, advantages, and challenges by using biofuels, in comparison with fossil fuels.

1. Introduction

For thousands of years, humanity has used solid fuels involving several types of organic materials originated from many sources, such as decomposed hydrocarbons in solid form, to produce power and heat by combustion [1].

According to the International Energy Agency (IEA) [2], 41% of the world's electricity comes from charcoal burning. A major current challenge is the search for technologies that could replace this charcoal with clean fuel sources and could possibly produce solid alternative fuels from different organic waste. Among the current types of solid biofuels, pellets, briquettes, wood chips, wood, and biochar stand out [3].

Such organic waste, known as biomass, can be converted into energy using several thermochemical processes, where the choice will depend on the type and quantity of available material, the desired form of energy, environmental regulations, and economic conditions. Such processes can be classified as direct combustion, which involves the biomass direct burning, and several processes for conversion of biomass into energy products [4].

Waste conversion processes, by means of densification, compaction, and agglomeration, according to Ferreira et al. [5], provides a number of advantages when compared to direct burning, especially regarding storage, handling, increased density, and calorific value.

Mineral coal is one of the most commonly used solid fuels in the energy chain. However, concerns regarding costs, as well as the impact on climate change resulting from the greenhouse gases generated by its combustion, have created a favorable scenario using and producing solid biofuels from residual raw materials.

Considering this context, this paper aims to approach the current scenario and the prospects of the solid biofuels in Brazil, together with the theoretical contextualization regarding the use and importance of mineral coal, charcoal and other solid biofuels in Brazil, due to the vast agricultural and forestry extension, this country annually produces significant amounts of solid biomasses.

2. Literature review

The world economy is still heavily dependent on fossil fuels; however, the unstable prices and the need to reduce pollutant gas emissions has been promoting the use of renewable energy sources. Thus, energy from wood, and waste in general, has come to play an important role in this scenario reducing thus the use of non-renewable fuels and being the same presented as a sustainable method [6].

Wood, traditionally called firewood, was one of the first energy sources used by humans, used in early times for cooking and warming. As society evolved, wood started to be used as solid fuel and to make fuel gas used in the generation of thermal, electrical, and mechanical

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energy. Today, it is still part of the world energy matrix, mainly used in domestic cooking and industry, and its use in each country varies according to the level of economic development, environmental issues, availability of forests, and competition with other energy sources [7].

Due to the increasing need for power generation and for the mitigation of global and local impacts as well as to the large volume of solid waste generated, a favorable environment has been created for application of these raw materials as energy sources. Using these materials as alternative energy sources would, at the same time, increase the supply of biofuels, enhance consumer's confidence, minimize environmental impacts, and rationalize waste management.

The advantages regarding the use of solid biofuels are environmental, social, and economic, once that the raw materials used to synthesize them are natural biomass originating from agroindustry. This means low cost, separation from the food chain, and management of the great volume of 'waste' biomass produced by agriculture. It would also provide the benefits of reducing climatic change (i.e., CH_4 and CO_2), pollutant emissions (e.g., NOx and SOx), and the use of fossil fuels. At the same time, this approach diversify the energy matrix, improve energy security, and generate jobs and income [8,9].

2.1. Feedstock

The feedstocks used for solid biofuel production are composed of lignocellulosic chemicals, classified as agricultural biomass. These are generated from oilseeds and oleaginous fruits, miscellaneous grains, medicinal plants, straw and fodder (e.g., chopped, ground, and pressed cereal chaff and straw). There are many agroindustrial types of biomass, including food and animal industry waste and by-products, including meal, ground parts from milling, pulp, bagasse and other wastes from sugar and alcohol production, oil cakes, feed pelleting waste and forestry biomasses. There is also forest biomass, such as wood and charcoal, firewood, trunks, branches and sticks, particulate coniferous and non-coniferous wood, wood sawdust, wood waste, briquettes and chipping manufacturing waste, bark from charcoal production and raw or debarked wood (e.g., oak, eucalyptus, pine) [10–13].

However, Đurišić-Mladenović et al. [14], categorize the biomass used to obtain wood solid fuel, which include materials from conventional forests and plantations, and non-wood ones as well (e.g., by-products of agricultural and agroindustrial processes).

Forests with eucalyptus and pine plantations stand out in Brazil because they represent a major source of energy in the industrial production chains and productivity varies according to crop management methods and various factors (e.g., vegetation type, plant density, altitude and latitude of the location, land relief, precipitation, humidity, wind, water and nutrients availability). In Brazil, considerable portions of commercial eucalyptus and pine plantations are located in regions subject to longer or shorter drought periods, and usually in regions with low-fertility soils [15–18].

According to Mood et al. [19], lignocellulosic materials have in their structure mainly cellulose, hemicellulose, and lignin, with lower amounts of ash and other compounds, as illustrated in Fig. 1.

According to Embrapa [22], Brazil has the potential to process more than 500 million metric tons of lignocellulosic waste originating from the agrosilvopastoral sector, as well as of raw materials that originate from other activities. The viability of the use of this waste as an energy source in the production of solid biofuels relates to equipment, transport, and places where the biomass is generated. Therefore, it is necessary to analyze the costs involved in its use, to make the process feasible, and to increase the participation of biomass in the Brazilian energy matrix [23].

Brazil is one of the main producers and exporters of agricultural products in the world, which is possible due to its rich tropical heritage. Biologically diverse land contributes to the production and the climate of certain regions. These are factors that, together with agricultural modernization, directly influence the intensity of agricultural practices and the increase in grain and food production in general. Since then, agroindustry has become responsible for the primary food processing, reporting increasingly numbers not only concerning the productive process but also on the waste generation [24].

2.2. Main Brazilian agricultural crops and their waste

The current debate over "fuel vs. food" intensifies the national and global interest in the use of agricultural waste in the biofuels production. This has led to a scenario in which agriculture provides both, without causing scarcity and competitiveness between fuel and food [25].

Based on data published by the Ministry of Agriculture, Livestock, and Food Supply [26], and by the Food and Agriculture Organization of the United Nations [27], among the main crops grown in Brazil, the following stand out: rice, beans, soybeans, corn, wheat, and sugar cane. Table 1 shows the data concerning the cultivated and the harvested area per Brazilian region in hectares, and the total harvested production (tons) based on the information published by IBGE [28], regarding the State Agricultural Production. The amount of waste generated for each of the crops was estimated taking into account the percentage of by-products created during processing for each culture type [29].

The diversity of crops and the quantities produced in each region, varies depending on the climate, soil, planting time, planting density, and seasonality [30]. In Southern Brazil, soy is the most cultivated crop, invariably generating more waste. Northeastern soils are used mainly for corn crops, and according to Costa et al. [31], corn culture has one of the highest percentages of waste production: approximately 620,000 tons in 2012 (Table 1).

According to Espíndola and Cunha [32], soy prevails as an agricultural product in terms of Brazilian exports and is also responsible for increasing the national grain harvest. This indicates that this crop is the leader in large-scale agriculture in Brazil, which is the second largest producer and first exporter of soybeans in the world. Soy corresponds to 49% of the area planted in grain in the country [26], and provides a high volume of hulls, straws, meal, and cake from oil extraction [33].

The Midwest is the dominant soybean producing region in Brazil, with (in 2012) an area under cultivation of 9,014,957 ha, and generating 19,126,996 tons of waste. The literature mentions, among the applications of such waste, its use as a fertilizer, soil conditioner, animal feed, feedstock for ethanol production [33], adsorbent for water purification [34]. enzymes synthesis [35,36], raw material for composting [37], and brick production [38].

In the field of dendroenergy and solid biofuels, these wastes are used as feedstock for pyrolysis to obtain syngas and bio-oil [39,40]; for gasification [41,42]; and to obtain biochar [43–45].

According to Embrapa [46], in addition to soybeans, maize (corn) is a major contributor, accounting for about 80% of the grain production in Brazil. The definitive difference between these two crops is the fact that much of the soy produced is exported, while the corn production is aimed at domestic supply. Corn production has grown at 3% per year, and accounted for 0.4% per year increase in the area of corn plantation. In the country, corn is grown in two different seasons, the first cultivated in summer and the second during the winter, adopting no-tillage techniques and with or without crop rotation [47].

Among the corn producing regions in Brazil, the South stands out as the largest producer, with 4,850,976 ha cultivated in 2012, production of 24,020,568 tons of corn, and generation of 13,931,929 tons of waste (Table 1). According to Owamah and Izinyon [48], this waste includes straw, hulls, cobs, meal, leaves, and grain.

According to the literature, corn lignocellulosic waste can be used as feedstock in anaerobic co-digestion for biogas production [48]; for direct combustion for heat generation, using the ash in construction due to its high silicon dioxide concentration [49]; for benzyl alcohol

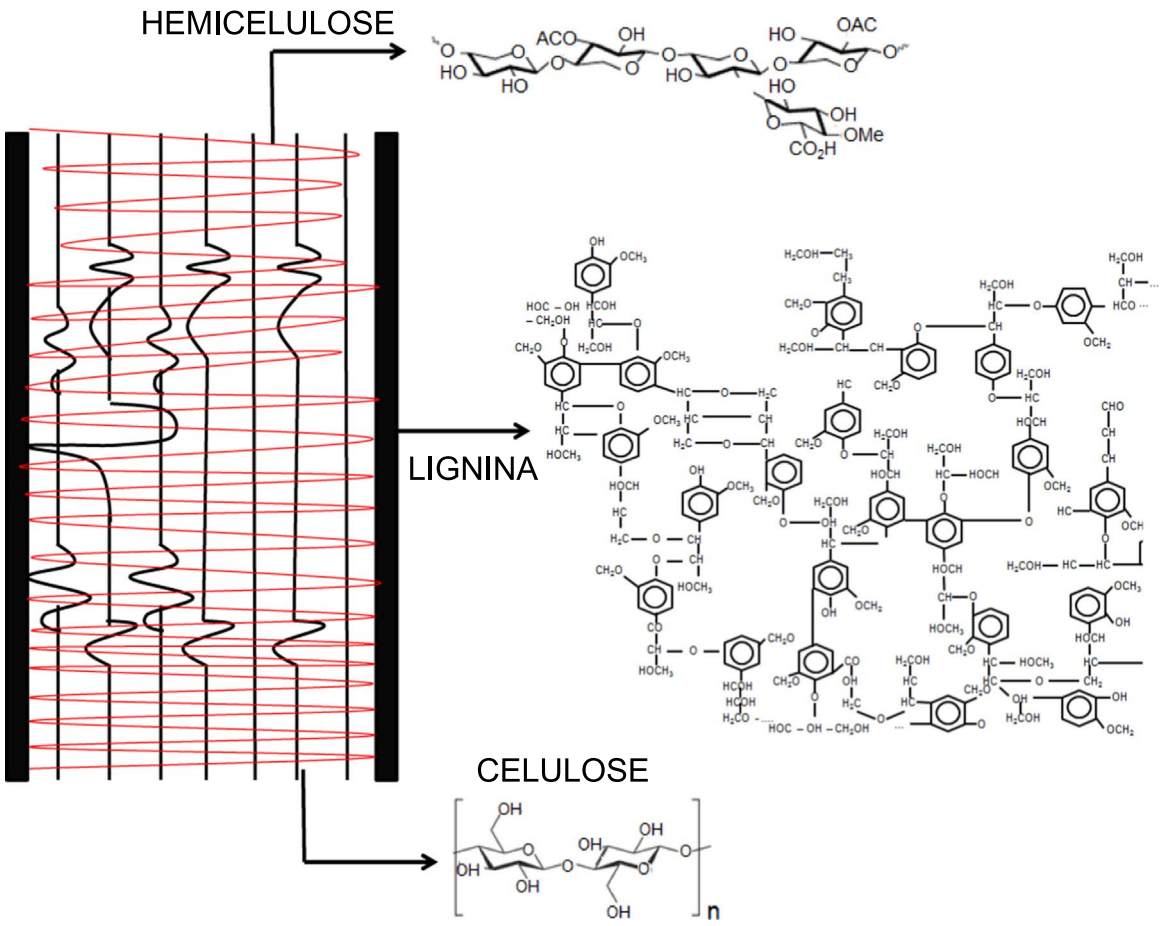

Fig. 1. Illustration of the main components of lignocellulosic materials (Adapted from [20,21]).

synthesis [50]; and as adsorbent material [51].

Among several applications as solid biofuel, reports indicate the use of husks, cobs, and corn stover in direct combustion for heat generation [48]; as binder in pellet synthesis [52]; as raw material for pellet manufacturing [53]; in gasification to obtain gas and charcoal synthesis [54]; for hydro char synthesis by carbonization [55,56]; and in pyrolysis to obtain charcoal [57,58].

Regarding the terms used, it is necessary to differentiate coal from charcoal, hydrochar, and biochar.

According to Aspergis and Tsoumas [59], Kambo and Dutta [60] and Grammelis et al. [61], mineral coal has fossil origin and is mainly used for the energy production by combustion. It is estimated that the reserves of this fuel will have exhausted 130 years' time. The use of coal grew exponentially, along with industrial development, which is due to the fact that coal is the most economic fossil fuel.

Charcoal is defined as a solid product rich in carbon, obtained by biomass carbonization, thus renewable.

The main differences between hydrochar and biochar are the pretreatment conditions of the biomass and the process applied. While hydrochar is synthesized from a solid mixture contained high water content (hydrothermal carbonization), biochar is obtained by dry carbonization (pyrolysis).

Concerning the rice crop, data published by Conab [62] indicates an increase of 2.6% in domestic production in relation to the 2014 harvest, hitting the mark of 12,499 million tons produced in Brazil in the harvest of 2014/15. Rio Grande do Sul stands out as the state with the highest productivity.

Table 1 shows, based on the calculation of waste generated, that the amount in the southern states of the country is about 1,303,086 tons, originating only from rice processing.

Huskis the main biomass generated. It represents 20% of the rice dry weight and is mainly composed of cellulose, hemicellulose, lignin, and silica; with small amounts of resins, essential oils, and extractives [63,64].

Due to the high silica content it is not used in food industry and it is widely targeted as an alternative heat source in many industrial processes: electricity generation in power plants through direct combustion [65]; feedstock in the biochar synthesis along with other biomass types such as cane bagasse [66]. Rice husk is also subjected to processes that produce activated carbon substrates, which are then used as adsorbents for the removal of pollutants in aqueous phase [67], and has potential uses in ceramic materials [68].

According to FAO [69] sugarcane is one of the most cultivated crops in the world and Brazil is the largest producer, followed by India and China. Brazil also stands out with the greatest production of sugar and ethanol. Although more than 50% of the production of this semi-perennial crop is concentrated in São Paulo, it is cultivated in all Brazilian regions [70].

In Brazil, the Southeast region is the largest sugarcane sower, out of which 6,685,058 ha were planted in 2012, with production of 481,277,697 tons, and generation of 144,383,309 tons of waste (Table 1). According to Silva et al. [71], it is estimated that the bagasse from the sugarcane agroindustry corresponds to about 280 kg per ton of crushed cane, that is, 30% of the total. Besides this waste, significant amounts of vinasse, filter cake, straw, and ashes are also generated.

The literature indicates that cane bagasse can be used as feedstock for the production of second generation ethanol [72,73]; for incorporation into polymer composites [74]; in anaerobic digestion for methane production [75]; and to obtain antioxidants [76] and activated carbon [77].

Table 1
Data of energy crops and estimated amounts of waste generated in the processing of rice, sugarcane, corn, soybeans and wheat (Data: IBGE [27]).

Regions of Brazil	Planted area (ha)	Harvested area (ha)	Total production harvested (t)	Waste generated (t)
Rice				
South	1,151,160	1,145,022	6,515,432	1,303,086
Southeast	72,145	71,495	294,092	58,818
Midwest	437,409	434,989	1,164,863	232,972
Northeast	741,675	732,277	1,024,557	204,911
North	465,535	460,760	1,029,456	205,891
Sugarcane				
South	717,191	715,698	49,554,465	14,866,339
Southeast	6,685,058	6,667,584	481,277,697	144,383,309
Midwest	1,806,738	1,798,610	132,490,492	39,747,147
Northeast	1,200,286	1,192,919	69,272,542	20,781,762
North	62,896	62,756	4,560,528	1,368,158
Corn				
South	4,850,976	4,808,867	24,020,568	13,931,929
Southeast	2,333,031	2,318,636	10,102,250	5,859,305
Midwest	3,387,938	3,381,193	13,522,338	7,842,956
Northeast	2,955,844	2,779,043	3,130,962	1,812,273
North	536,482	533,125	1,070,078	620,645
Soybean				
South	8,283,922	8,282,999	22,917,251	16,729,593
Southeast	1,411,032	1,410,282	3,842,890	2,805,309
Midwest	9,014,957	9,014,157	26,201,365	19,126,996
Northeast	1,455,734	1,452,880	3,909,240	2,853,745
North	455,075	454,281	1,167,287	852,119
Wheat				
South	1,680,633	1,679,868	3,853,557	2,312,134
Southeast	55,739	55,739	149,970	89,982
Midwest	45,796	45,727	104,088	62,452
Brazil	**49,807,252**	**49,498,907**	**861,175,968**	**298,051,832**

According to CONAB [78], in Brazil's 2009/2010 sugarcane harvest 78,222,608 tons of bagasse were generated; out of which 71,595,078 tons (91.5%) was intended for use as solid biofuel in energy co-generation. This shows that this waste product is widely used in energy production.

There are also reports of research using bagasse as feedstock for pyrolysis processes to obtain bio-oil and activated carbon [79]; to generate electricity [80–82]; and in gasification for syngas production [83].

In addition to bagasse, sugarcane straw (leaf matter) is another lignocellulosic waste generated in large quantities. The leaves are stripped during the cutting of the sugarcane, containing small amounts of juice, and are usually left in the field after harvest [84].

Sugarcane straw can be used for electricity generation, as a feedstock for the production of second generation ethanol [85], and for thermochemical decomposition processes used to obtain charcoal [86].

Wheat, according to Manoeli et al. [87] and Souza et al. [88] is the main winter crop in southern Brazil, and this culture accounts for approximately 30% of world grain production.

CONAB's data [62] indicated that for the 2015/2016 crop, it is estimated 2448.8 ha, of area planted with wheat, being that in January 2016 the country imported 378.4 thousand tons. In 2012 (Table 1), the South produced 2,312,134 tons of waste from wheat culture, including hulls, mulch, and meal.

Among the uses of this waste are wheat straw composting [89], bioethanol production [90] and [91], and feedstock in anaerobic co-digestion [92]. In solid biofuel synthesis, it is used as feedstock in hydrocarbonization to obtain charcoal [93]; in the production of fuel pellets [94,95]; in pyrolysis processes [96]; and to obtain syngas [97,98].

The constant motivation to use alternative feedstocks, such as agricultural waste for the production of biofuels as substitutes for fossil fuels, comes from the first oil crisis in the 70s. Bioengineering has been assessed as a viable and promising alternative process in the medium and short run assuming that it will stand out in the global energy matrix in the upcoming years. This is projected to meet mainly the transport sector demand.

Fig. 2 shows 2014/2015 harvest data and forecasts until 2024 concerning the production of wheat, rice, cereals in general (soybean, maize), and sugarcane production in Brazil, all crops from which it is likely that bioenergy could be produced.

The linear increase in the prospects for the national production of grains and grass (sugarcane) is remarkable. The improvement of planting techniques, crops, and variety of species, along with new technologies and population growth, are the main factors propelling the general increase in the production.

Unlike for other crops, wheat suffered a significant drop in production in 2015. According to SEAB [100], after the largest harvest in history in 2014, the state of Parana showed a decrease of at least 3%, which corresponds to an area of 1.35 million hectares.

Wheat is the second most produced cereal in the world. Table 1 shows that the southern region of Brazil is the largest producer of this

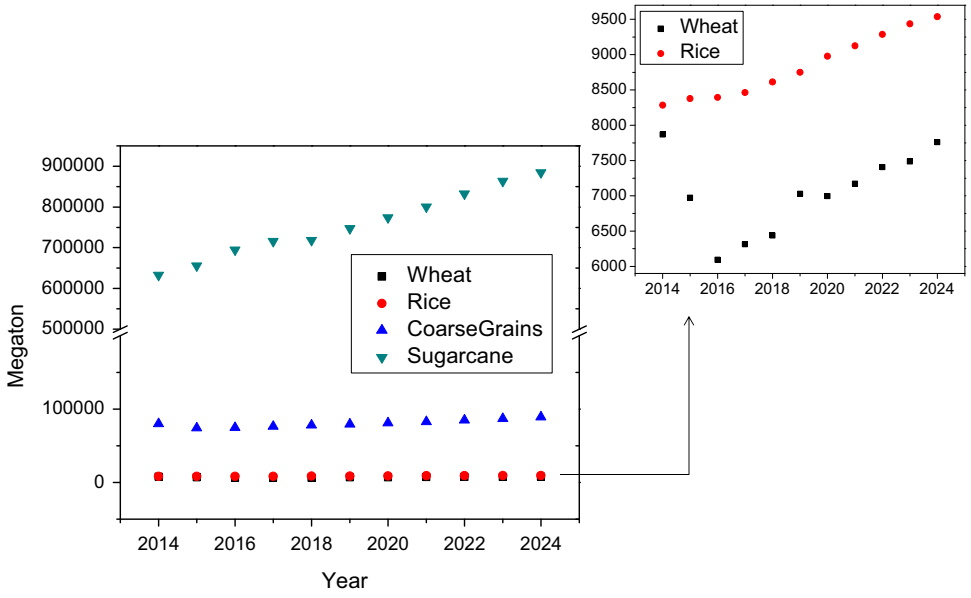

Fig. 2. Prospects of production of some crops by 2024 (Data: OECD/FAO [99]).

crop, contributing to about 90% of the Brazilian production, thus the decreased planting in these areas directly impacts the total production by Brazil and in the economy. One of the characteristics of wheat culture is year-to-year fluctuation of the production and area of cultivation, which comes from expectations of profitability, losses from pest attacks, and climate issues. The productivity growth forecast is 24% for the 2022/2023 harvest, in relation to the figures for 2013 [101].

According to FIESP [101], and as shown in Fig. 2, it is estimated that for the next ten years, the Brazilian production of agricultural commodities will grow gradually. Regarding sugarcane culture, so that the same meets the sugar and alcohol consumption growth demand and exports at the 2023/2024 harvest, it will be necessary for Brazil to achieve a planted area of about 10.5 million hectares, and the southeast region will represent 23% of this crop. Brazil is the main sugar supplier to the international market, currently exporting approximately 50% of total production, mainly to Russia, Iran, and China.

According to Bain & Company [102] and FAO [103], the agricultural production growth trend is not only national but also global. Sector growth of 3.6% per year is expected, which would increase world GDP about 40%, and significantly increase the production of agricultural waste. This outlook comes from the attempt to overcome the current economic crisis, from the increase in the number of consumers as a consequence of the population growth we have been experiencing, along with increase in the daily food consumption per capita, new investments, human capital development, and increased demand for fuel.

The versatility, availability, and numerous forms of agricultural waste reuse makes it possible to use this feedstock as a renewable resource [104].

2.3. Main Brazilian forest crops and their waste

According to Chandra et al. [105], wood, crops, aquatic plants, algae, and agricultural waste, waste from the timber industry, the organic fraction of Municipal Solid Waste (MSW), and food processing are the most important sources of energy and biofuels.

Table 2, shows harvest data of eucalyptus and pine (m^3) (the main crops involving reforesting in Brazil) by region, based on data released by IBGE [106], about tree extraction and forestry. The amount of waste generated for each of the crops was estimated taking into account the percentages of waste inherent in the type of processing used for each type of culture [29].

Brazilian forest products are considered competitive in the international market, and exports have grown steadily in recent years. Eucalyptus and pine plantations in Brazil are mainly intended for sustainable production, to meet domestic demand for thermal power generation in several industrial sectors [107].

Based on data published in the latest report of the Brazilian Planted Forests Producers Association [108], eucalyptus and pine plantation areas in Brazil reached about 6.66 million hectares (a 2.2% increase compared to 2011). Of this total area, the eucalyptus plantation occupied 76.6%, while pine plantation occupied 23.4%. According to IBGE [106], the area planted in eucalyptus forest reached 6,951,145 ha, and the state of Minas Gerais represents about 1,713,576 ha of this. On the other hand, pine forests occupied 2,048,284 ha in Brazil.

Table 2
Total production data collected and estimated waste generated of Brazilian forests of pine and eucalyptus (Data: IBGE [102]).

Regions of Brazil	Total production harvested (m^3)	Waste generated (m^3)
South	24,218,684	3,632,802
Southeast	7,760,358	1,164,053
Midwest	6,529,713	979,456
Northeast	1,627,728	244,159
Brazil	40,136,483	6,020,470

The region with the highest concentration of forest plantation is the South (Table 2), with a total of 24,218,684 m^3 of harvested crop, which generates approximately 3,632,802 m^3 of waste that can also be used as an energy source. One of the benefits of these two forest species is that they do not require high-productivity areas (i.e., they can be grown on marginal or degraded land and often in low-productivity sandy soils); therefore, they do not directly compete for the land necessary for food crops planting [109].

Among the examples of applications of these two tree cultures in biofuel production that could be mentioned, are pellets obtained from pine wood waste [110], eucalyptus-shoot pellets [111]; and briquettes of eucalyptus and pine sawdust waste [112].

2.4. Solid biofuel production routes and technologies

The use of biomass in nature (i.e., not from cultivated or industrial areas) can cause problems regarding storage, transport, handling, and processing [113]. Thus, some strategies and technologies have been developed with the aim of converting these feedstocks into secondary fuels.

These technologies relate to biomass densification, which has the purpose to increase the energy per mass unit. This facilitates transport and storage, and creates a more uniform burn in industrial equipment such as boilers, furnaces, and gasifiers [114,115].

According to Goyal et al. [116], thermochemical conversion processes involve the gasification and liquefaction of biomass, and its conversion to hydrocarbons at high temperature and pressure. These processes are responsible for the production of fuels with higher calorific value; in which the choice of the conversion process depends on the desired final energy, quantity and type of biomass, and the economic and environmental conditions. Among the different thermochemical routes are combustion, gasification, pyrolysis, carbonization, and torrefaction. For the processes of both gasification and liquefaction, in which then devolatilization is the first stage of both processes, and results show a loss of about 80% of the total weight of the biomass [13,117,118].

2.4.1. Pyrolysis

Pyrolysis comprises devolatilization, that is, thermal decomposition of the material in the absence of oxygen, which it is rapidly heated to temperatures ranging from 350–550 to 700 °C, resulting in a liquid product (bio-oil) that is a mixture of complex organic compounds derived from lignin, gas (syngas), and solids (biochar) [119,120].

On the other hand, according to Tripathi et al. [121], pyrolysis occurs at temperatures from 400 to 1200 °C. In this paper, pyrolysis is characterized as an effective and efficient process for obtaining energy (in the forms of charcoal or bio-oil) from biomass. This is a thermochemical process in which the chemical constituents of the biomass are thermally degraded while in an inert gas.

Different process conditions, such as temperature and heating rate, have no impact on the weight loss of the biomass by volatilization, but really lead to the production of different product portions. Biochar formation is minimized at higher heating rates, and in contrast, gas products are formed at high heating rates and high temperatures (above 700 °C). Bio-oil is favored by fast pyrolysis at 550–600 °C [120–123].

The major benefit of pyrolysis compared to other technologies, is the bio-oil production as an intermediate product, which can be transformed into fuels for the transport sector (e.g., diesel and gasoline), or as feedstock for the chemical industry. Still, it is considered a flexible process in relation to the range of feedstocks that can be used, the diverse operating conditions, and the ability to obtain products with low levels of sulfur and NOx emissions. The yield and quality of

the pyrolyzed material depend on parameters such as heating rate, temperature, particle size, solid residence time, and residence time distribution. Fluidized bed reactors are recommended for this process [121,123].

Pyrolysis can occur in two ways: fast or slow. When slow, the process is conducted at low heating rates and temperature < 500 °C and with long residence time, leading to formation of a smaller quantity of liquid and gas products, and a larger quantity of charcoal. On the other hand, fast pyrolysis provides a greater liquid-product yield through the rapid heating of the biomass at temperatures > 550 °C. It is considered a simple technique that significantly benefits the logistics of conversion of the obtained product into final products. It is a non-selective process which accepts a wide variety of lignocellulosic materials as feedstock, including pig farm and agroindustrial waste, in general [116,122,124].

2.4.2. Gasification

Gasification is another possible thermochemical route. It involves the conversion of solid biomass into a gas mixture from partial oxidation at high temperatures (800–900 °C). The delignification of lignocellulosic material is not necessary. Syngas is the process final product and it can be converted into other chemical feedstocks by reforming processes, into fuels by the Fischer-Tropsch method, or used to obtain hydrogen for fuel cells [125,126].

The gasification reaction product is composed of hydrogen, carbon monoxide, methane, and carbon dioxide. Depending on the type of gasifying agent (air, steam, and/or oxygen) injected, some types of light hydrocarbons are also obtained. Gasification technology is already widespread; however, the main challenge is to use it commercially for converting solid biomass. It is necessary to combine the reaction operating conditions and the characteristics of each material, in order to optimize product composition and process efficiency; and to reduce the formation of undesirable products [6].

According to Lora and Venturini [127], among the most common types of gasifiers, the fixed bed, double stage, fluidized bed; and entrained flow arrangements stand out. Among the variables that must be controlled during the gasification process, there is the equivalence ratio (defines the proportion of fuel burned by the gasified quantity); temperature (should be at appropriate level for the carbon in the biomass to be transformed completely. It influences the concentration of the gas compounds produced.); gas production capacity (relates to the equivalence ratio and the residence time); and the gasifying agent (influences the gasification efficiency, composition, and calorific value of the gas produced).

According to Goyal et al. [116], biomass gasification involves biomass conversion into a gas mixture (in an inert gas and at high temperature) from biomass partial oxidation, according to the following reactions (1)–(4).

$$C+O_2 \rightarrow CO_2 \quad (1)$$

$$C+\frac{1}{2}O_2 \rightarrow CO \quad (2)$$

$$CO+\frac{1}{2}O_2 \rightarrow CO_2 \quad (3)$$

$$CO_2+C \leftrightarrow 2CO \quad (4)$$

Methane and hydrogen are formed simultaneously by the thermal cracking of organic material (5).

$$CO_2+4H_2 \rightarrow CH_4+2H_2O \quad (5)$$

2.4.3. Carbonization

Carbonization is a biomass thermochemical treatment carried out in an inert gas and at temperatures between 400 and 500 °C. Thermal decomposition of the material occurs in the absence of air or with controlled amounts of oxygen, during which it undergoes physical, chemical, and structural changes depending on the temperature employed. The main objective of the technique is carbon enrichment for energy-use purposes, although it results in a low yield of solids. In addition, there is also the generation of non-condensable gases, organic liquids, and steam [128–130].

During carbonization, biomass macromolecules break, devolatilization and deoxygenation take place and provide yields of solids equal to about one third of the initial weight of the biomass. Polysaccharides such as cellulose and hemicellulose tend to form volatile products, and the lignin is transformed into coal after C–H and C–O bonds break, obtaining a carbon-rich solid [131,132].

According to Yahya et al. [133], biomass carbonization also results in an increase in the porosity of the material obtained by the selective elimination of the most reactive carbon from the structure. The temperature applied to the process, the heating rate, the inert gas flow rate, and the conduction time, all of them impact the characteristics of the charcoal produced. Temperature increase results in the decrease of the concentration of volatiles and increases the concentration of fixed carbon and ashes.

2.4.4. Torrefaction

As in carbonization, the objective of torrefaction is the formation of charcoal by heating the biomass under an inert gas, at atmospheric pressure, with low heating rates, and at temperatures ranging from 200 to 300 °C. Most of the hemicellulose is decomposed, while cellulose and lignin are less affected. Charcoal (characterized by fine particles and ash), condensable liquids (particularly water, organic compounds, and lipids) and mixtures of non-condensable gases (CO, CO_2, H_2, and CH_4) are the products of this process [134,135].

There is a significant mass loss mainly due to the material decomposition, which may range from 50% to 85%. Higher calorific value, higher energy density, lower C/O ratio and moisture level, greater impermeability, more reactivity, and uniform biomass properties are some of the advantages of the torrefied product, compared to biomass in its natural condition [136,137].

According to Bach and Skreiberg [138], the main objective of the torrefaction process is the production of solid products with improved chemical and physical properties (compared to raw biomass). The final product is characterized by its higher calorific power, change in its hygroscopic quality to become hydrophobic, and by better granulometry of the final fuel.

2.5. Densification technologies

Agricultural waste is the greatest potential source of energy in Brazil due to its vast territory, production of several grains, and access to other potential inputs. However, these hulls, straw, and by-products in general, are burnt without optimizing their energy efficiency or generating the entire amount of energy available. Bearing in mind the best energetic use of the material, there are biomass densification technologies, which aim to reduce granulometry and increase calorific value, facilitating the transport and handling of solid biofuels. Among the process types are briquetting, pelleting, and chip production [114].

Lignocellulosic materials densification for the production of solid fuels is not recent. In 1848, an American, William Easby, patented in the United States a method of small charcoal conversion in solid lumps, called briquettes, by the use of pressure. Therefore, low value-added materials could then be used as fuel in steamships and ovens for food preparation. This technology is widespread in Europe, and its use in Brazil comes from Germany. On the other hand, other authors state that such technology was inherited from cave men who clustered waste from fires with animals blood to be reused in future fires [139].

According to Wongsiriamnuay and Tippayawong [53], densification affects the properties and quality of the fuel, and the variables controlled during the process (e.g., pressure, temperature, speed,

time), influence the density and durability of the final product. High temperatures provide greater durability to the densified material but require greater energy consumption and higher operating expenses.

Energy density increase per unit volume; easier handling, transportation, and storage; improved combustion; lower particle emissions; lower volatility, smaller size, greater density, and uniform quality are some of the advantages of biomass densification [140].

2.5.1. Briquetting

Briquetting technology involves the conversion of biomass into high density solid biofuels that are easy to use, handle, store, and transport, which also produces a high-energy burn with lower emissions. Briquettes can be made from a variety of waste materials such as wood sawdust, paper, leaves, grass, rice hulls, bagasse, mulching, and general agricultural waste [141,142].

The process consists of feedstock compression, drying, cutting, formation of briquettes and cooling. Devices such as pistons, screws, hydraulic and roll presses can be used, with or without binders (organic or inorganic). Lignin itself, or biomass protein, can serve as a binder [143,144].

In the process of briquetting, parameters such as pressure, temperature, and moisture level directly influence how the briquettes are obtained and their final quality. The binder must have plasticity and elasticity to be effective in the fuel production, and its use improves density, durability, and resistance to shearing. The literature indicates tests have been done using solid carbon, starch, bentonite, and plastics as binders, in proportions of 2–15%, in relation to the mass of the feedstock [144–147].

In a study carried out by Li et al. [143], there was production of briquettes from corn cobs and leaves, without any binders. The briquettes presented a 30 × 30 mm cross-section cubic form, 50–150 mm long, with density of 1484 kg m^{-3}. The initial feedstock moisture level was kept between 15% and 30% and the final moisture level from 8.4% to 10.27%.

Kaliyan and Morey [148] used a mixture of 80% grass and 20% corn straw in the production of briquettes. These were preheated at 100 °C to activate the binder present in the material. The authors observed a significant increase in briquette quality, especially regarding lower cost from not using chemical binders.

2.5.2. Pelleting

Pellets can be made from wood sawdust, grasses, and the waste of energy crops. They have 2–3 cm length cylindrical shapes and are produced at high pressures and temperatures, conditions under which lignin is able to work as a binder. The energy of the pellets can increase from 9 to 18 MJ m^{-3} in relation to natural biomass, and the volume can be reduced from 8 to 10 times [3].

Pelletized biomass is characterized by low moisture level, mechanical durability, high density, minimum ash levels, light brown color, and small size, which makes it easy to transport, store, and handle. Feedstock, humidity, extrusion type, speed, temperature, pressure, and drying method are some of the factors that influence the characteristics of the pellets produced. The equipment used in the pellet production may be the worm screw extruder type, also known as the Archimedean screw, or roller extruder. The choice for one or another is based on the quality and characteristics desired, as well as the material destination [3,149].

Home, commercial, and industrial sectors use pellets for power generation. At small scale, they are used in the heating of homes, buildings, pizzerias, bakeries, and stores; and on a larger scale in plants and industries. These fuels are considered low-emission and renewable when they are produced from waste or wood. These environmental benefits, combined with the high energy level, low humidity, and ease in transport and storage, are the reasons for the fast growth of the global pellets market, both in terms of production and consumption [150,151].

Unpinit et al. [152], produced pellets in Thailand from six diverse biomasses: bamboo sawdust, eucalyptus sawdust, corn cobs, tree branches, palm fiber, and grass. The materials were dried for three days for moisture reduction and were subsequently ground and sieved, selecting the material with granules smaller than 2 mm. The final pellets obtained had a diameter of 1.3 cm, and among the analyses carried out the authors called the attention for the increase in the solid biofuel density. This analysis is representative of the weight per pellets volume unit. Low density pellets provide poor combustion, resulting in low thermal efficiency. During biomass briquetting, as the pressure increases from 55 to 139 MPa, the final bamboo sawdust fuel density increases from 975 to 1120 kg m^{-3}, indicating and improvement in burn quality and a higher LHV (low heating value).

2.5.3. Wood chips

Firewood is a bulky form of biomass, hampering its use in small heating systems. Thus, there is potential for using 'wood chips', which are small pieces of tree trunks and branches cut in a chipper. Their sizes are determined by their intended final use [3].

However, chips can lose significant weight of dry matter and energy level during storage. Moreover, its moisture level in certain periods of the year may reach 50–60%, which reduces the maximum combustion temperature and thus the thermal efficiency. In order to minimize chips deterioration during storage, biomass can be torrefied or dried prior to use [153].

2.6. New technologies

According to Pinto et al. [111], the development of new technologies is of great importance for obtaining solid biofuels intended to reduce CO_2 emissions, facilitating its storage and capture by agricultural crops. It is also important to increase the energy efficiency during its use, especially by reusing low cost feedstock, along with feasible and effective technologies.

New technologies for obtaining biofuels are being analyzed in order to improve their performance and increase the energy efficiency from their burning. Hydrocarbonization is one of these technologies [3].

2.6.1. Hydrocarbonization

Taking into account its low cost and high yield, hydrocarbonization is considered a promising technology for using biomass with high moisture levels, and for reducing the energy costs for drying cellulosic materials, urban solid and agricultural waste, and paper scraps [154,155].

Hydrothermal carbonization is a thermochemical process used to obtain high calorific value hydrocarbon from a raw biomass suspension in aqueous media, at moderate temperature (180–205 °C) and pressure. The product to be obtained can be used for fuel, catalysis, water purification, and carbon sequestration. It is morphologically regular and its surface is rich in carbon [156].

For accepting highly moist feedstock with high ash content, hydrocarbonization proves to be advantageous when compared to carbonization. Hydrocarbonized fuel has superior energy density, greater hydrophobicity, and is easily friable (reduced to powder). Moreover, the technology required is simpler and has lower cost [156,157].

Gao et al. [158], used eucalyptus bark in the preparation of hydrochar in an autoclave at 220–300 °C and 4.4–6.0 MPa. This resulted in a high calorific value, uniform microparticulate product, with yield of 40% and calorific value of 29.2 MJ kg^{-1}.

2.7. National and world markets

The solid fuels market is quite diverse, both in the ways available to acquire products such as pellets, briquettes, and firewood, or for the local import/export purpose, and the sales price. According to Tavares

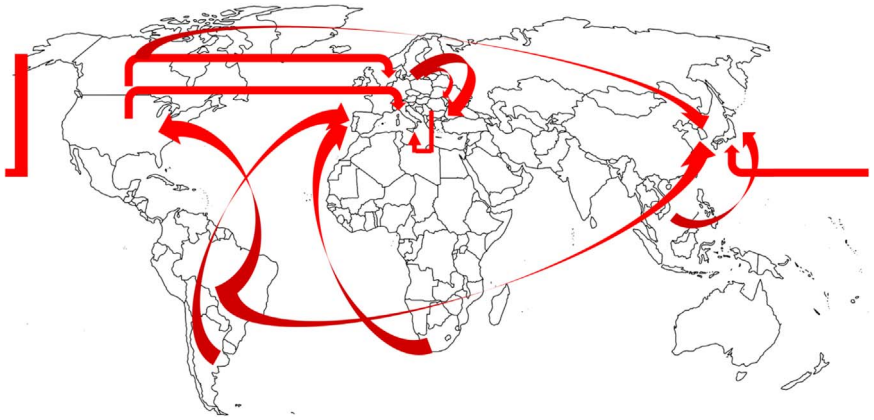

Fig. 3. Global export flow of solid fuels (pellets, chips and briquetes) (Data: IEA [2]).

and Tavares [159], despite their long tradition in forest and wood industries, northern European countries have not been able to meet their own energy demand and are importing pellets from countries such as Canada and the US, as shown in the global flow of exported pellets, briquettes, and chips (Fig. 3).

Based on data published in the International Energy Agency [2] and shown in Fig. 3, countries in the North and South America and in southern Africa have exported significant quantities of biofuels to Europe.

Possible reasons for the European market behavior concerning imports of biomass solid fuels come from European Union policies, which aim to reduce emissions of greenhouse gases, as well as their dependence on energy from petroleum and natural gas by 2020. The use of pellets as an energy alternative is effective in the fight against climate change, in addition to providing positive globalization and job creation [160,161].

According to Justin et al. [162], the biggest obstacle to leveraging the use of solid biofuels in the form of pellets is their high production cost and the fact that the relevant technologies are still in development. These obstacles have already been overcome. Portugal has been demonstrating developments in the biofuel industry for chipping since 2006, when the first pelleting plant was implemented, with production capacity of 100,000 tons per year. About 36% of Portugal consists of pine and eucalyptus (*Pinus pinaster* and *Eucalyptus globulus*) reforestation areas [150].

Table 3 shows the prospects for pellet production for 2020 in the international context. In relation to 2010, the forecast is that the production will grow from 105 to 305 million tons, due to the increase of energy demand in the transportation sector [163].

As shown in Table 3, North America, western Europe, and China rule the world's pellet production, and the majority of that production is exported to Europe, the biggest consumer [164].

In recent years, pellets have become a fuel of great importance in Europe, because feedstock densification facilitates transportation and use. These benefits have increased their application rate in the domestic market, in addition to subsidies and national policies that encourage the development of technologies. They are also subject to wide use in countries like Germany, Austria, and Sweden, which are consumers and exporters at the same time (Fig. 3). On the other hand, Denmark and Italy are only great consumers [165,166].

Table 3
Forecasts to Wood pellets production (× 1,000,000 ton year^{-1}) for 2020 (Data: Sikkema et al. [159]).

Regions	2020
North America	11,0
South America	4,4
Western Europe	13,0
Eastern Europe	3,3
Russia	1,6
Japan & Korea	1,1
China	10,0
Oceania	0,8

European Union policies for reducing greenhouse gas emissions and for maximizing the use of clean energy sources, combined with easy handling, good inventory, convenient transport by ship, low humidity, and waste reuse, are the main reasons for the use of pellets for energy production [164,167,168].

According to Keränen and Alakangas [169] the short-term pricing mechanism is influenced by the cost of feedstocks and long-term pricing by fuel costs, in relation to freight and currency exchange rates. This makes it essential to focus on efficient production and process optimization in the factories to be established.

In Brazil, the transition from heavy reliance on traditional biomass (wood) to a diversified and modern energy matrix took about three decades, being wood the main energy source in Brazil until 1973, when it was replaced by oil, firewood, and charcoal. Bio-fuel engineered based on sugarcane bagasse was limited to internal uses in sugarcane mills. Nowadays, solid biofuels are already used as thermal energy sources, especially in wood processing, and in pulp, paper, and cellulose industries, to meet the currently imposed sustainability goals [170].

According to Garcia [171], wood pellets are used for power generation and heating in the country, especially in pizzerias, in the states of São Paulo, Rio Grande do Sul, Rio de Janeiro, Minas Gerais, and Bahia; and generally in bakeries, laundries, swimming gyms, and hotels.

Nowadays, Brazil has 14 pelleting plants with production capacity of 500,000 tons per year, mainly installed in the South and Southeast. From the economic point of view, pellets are competitive when compared to natural gas and petroleum oils, and neutral in greenhouse gases emissions [171].

Data published in the last Brazilian energy review (2014) showed that 39.4% of the domestic energy supply has a renewable basis, of which firewood and charcoal corresponds to 8.1% and sugarcane by-products, 15.7%. Such values indicate Brazil's reliance on the use of these solid biofuels sources and feedstocks [172].

According to BEN [173], the domestic energy supply using sugarcane biomass has increased by 1.1% and wood and its by-products have increased by 0.6% compared to the previous year. This growth results from their use in thermal generation. The consumption of these energy sources happens mainly in the industry: 8.9% and 18.5% of the energy consumption matrix in this sector corresponds to the use of firewood and bagasse, respectively, while in the transport sector there is no use of these sources.

2.8. Use policies

In Brazil, there is no technical standard that specifies parameters for the manufacture and analysis that must be performed on manufactured solid biofuels. Thus, their physical and chemical properties can be determined by the specifications of the Brazilian Association of Technical Standards (ABNT) for coal, charcoal and activated charcoal, which can be adapted to any type of solid fuel. For example, to analyze the calorific value of pellets and briquettes, ABNT NBR 8633/84 can be used [174,175].

The Environment National Council, concerned with emissions, established the maximum limits of air pollutants in Resolution No. 436, dated from December 22nd, 2011. In this regulation, the limits of the total reduced sulfur, particulate material, NO_x (nitrogen monoxide and dioxide), and SO_X (monoxide and sulfur trioxide) were specified [176].

In Europe, because the use of solid biofuels is already widespread, certain rules are already set by European Standards (EN) defining such fuels as those originating from the following sources: wood waste (with the exception of those that may contain halogenated organic compounds or heavy metals), vegetable waste from agriculture, forestry and food processing industries, and fibrous vegetable wastes obtained from the production of paper pulp and cork waste.

EN 14961-1 established standards for pellets coming from wood, herbaceous plants, fruit, and blends of biomass, with parameters for size, moisture, ash, mechanical durability, additives, bulk density, calorific value, sulfur, nitrogen, and chlorine. For wood chips, this standard regulates dimensions, moisture level, ash, nitrogen, chlorine, calorific value, density, and deformation temperature parameters [177–179].

2.9. Solid biofuels vs. fossil fuels

Energy production using fossil fuels or waste combustion are the most used technologies, according to Pinto et al. [180]. However, when seeking to reduce pollutant emissions during combustion, using non-renewable sources tends to be rejected. The development of technologies to increase waste-fuel energy density generated from biomass could minimize these problems.

Coal gasification is a process that has already been established; however, due to the reduction of fossil fuel reserves, price volatility, and climate change, it is necessary to use solid biofuels or fuel/waste blends in co-combustion processes. This solves the problems with fossil fuels of inconvenience and dependence, and helps to resolve the waste disposal issues of agricultural, industrial, and forestry related to bio-waste [181].

According to Dincer [182], many kinds of plant products (e.g., agricultural waste, wood waste, bark, leaves, branches, and urban solids) might be used as feedstock for biochar production, being that such waste products are already available, and new technologies for extraction and production are not necessary, as it is the case with coal, which involves growing costs for obtaining and exploiting limited environmental resources.

Biofuels and solid fuels are mainly used for the generation of energy by combustion. Table 4 shows the data published by the IEA [183] related to the amount of energy generated from coal and biofuels in Brazil (2014).

According to the data, it is noteworthy that in Brazil, the use of charcoal is already higher than coal, which is due to the fact that the biomass energy density is comparable to that of fossil fuels, such as coal and petrochemicals [184].

As previously observed in Fig. 2, until 2024, a gradual increase is expected in the production of some crops and a concomitant increase in the generation of agricultural solid waste, in addition to the residues deriving from industrial activities. Increased production of solid urban waste is also expected. Therefore, larger volumes of biomass will be available for the production of bio-oil, synthesis gas, and solid biofuels.

According to Salazar et al. [185], the potential of a given region for the production of solid biofuels is related to the amount of solid waste made available, which mainly includes agricultural, forestry, and industrial waste. Jonker et al. [186] pointed out that one of the main advantages of using solid waste in the form of solid biofuels to produce energy by combustion relies on the ability to provide steam and electricity for agro-industrial processes, using low-cost waste.

Weldu and Assefa [187] state that most energy is still generated from coal, although the use of biomass is fundamental from an environmental point of view. This is due to an interest in increasing its use and consequently minimizing the exploration and intensive consumption of fossil sources. Singh [188] agrees with this information and states that the use of waste for energy production is an advantage from the economic and environmental points of view. This author also indicates that the combustion of coal with lignocellulosic waste provides a number of advantages related to increase in furnace efficiency, reduction of fuel costs, and minimization of nitrogen oxide and carbon dioxide emissions.

Table 5 shows the energy required to produce one ton of pellets derived from wood and coal waste, as well as the greenhouse gases emissions generated from such combustion processes [189].

It can be observed that both the energy required to produce one ton of pellets, and the greenhouse gases emissions generated by these combustion processes, are lower. Solid residues are already available and low energy costs are necessary for their production. However, the technologies for the extraction of coal require large amounts of energy; moreover, due to its fossil origin, gas emissions are higher.

Besides being used as biofuel for the production of electricity, unlike charcoal that has only energetic purposes, the biochar synthetized from lignocellulosic waste can also be used to adsorb contaminants and fertilize the soil (perhaps modifying its pH). This leads to a greater retention of nutrients by cation adsorption and reduction in methane and nitrogen oxide emissions [190].

2.10. Benefits and challenges

The employment of biomass and solid biofuels must consider two aspects: ways to expand and improve the basic knowledge on the composition and properties, and ways to apply this knowledge in optimal and sustainable ways. Knowledge of the composition of biofuels is essential and depends on several factors that define its properties, quality and possible applications, and information on issues regarding technology and sustainability; that must be reported for each type before use [8].

The main benefits of using pellets and briquettes in relation to natural wood and waste is their higher calorific value, greater stability

Table 4
Electricity generated by mineral coal and charcoal in Brazil at 2014 [184].

Energy source	Electricity (GWh)
Coal	26,754
Charcoal	45,994

Table 5
Energy use and greenhouse gases (GHG) of coal and wood pellet [189].

Fuel	Energy use (MJ)	GHG (g CO^2-eq)	Criteria emissions (g)				
			CO	NO_x	SO_2	PM	$PM_{2.5}$
Pellets (1 ton)	1437	137,531	204	692	800	246	111
Coal (1 ton)	3300	866,001	139	521	4290	1220	748

Table 6
Composition of coal and biochar [194].

	Fixed carbon (%)	Hydrogen (%)	Oxygen (%)	Nitrogen (%)	Sulfur (%)	Moisture (%)	Ash (%)	Volatile matter (%)
Coal	82.80	2.31	2.31	0.90	0.42	2.30	10.27	8.60
Biochar	91.60	2.27	1.95	0.38	0.02	2.30	0.57	19.10

during combustion, the ready waste availability, easy transport, storage, and handling; and lower cost of waste biomass. However, the greatest challenges are related to the installation of briquetting machines and pellet mills, adaptation of plant boiler furnaces so that these biofuels can be used, encouraging the use of the technology, and further improvement to cheapen production and consumption costs [191,192].

The use of biochar implies low emissions and higher energy density per mass unit during combustion; however, it requires high temperatures and long residence times to make it, which involves high energy expense. For biochar production to be viable, the energy contained in the final product must be greater than that spent in obtaining it, in other words, it must have a positive energy balance [123].

As for gasification, this technology has already gained ground in the business sector, although no project has operated long enough to reveal real data useful for assessing performance and costs. Research has focused mainly on syngas, seeking technologies able to operate with different types of biomass and able to advance gas cleaning, to remove specific impurities such as tar and alkali [127].

2.11. Overview and solid biofuel prospects

The use of solid biomass as energy sources has many advantages, because it can be obtained from wood, livestock, agricultural, or forestry waste. When using biomass, carbon monoxide emissions are reduced, because crops absorb the carbon emitted during combustion for foliar growth, and the turnover time of CO_2 cycling is significantly lower (5–10 years), when compared to fossil fuels (100 million years) [193].

Table 6 shows a comparison of the composition of coal and biochar [194]. Regarding the composition of both materials presented, it can be observed that the biochar has lower concentrations of hydrogen, oxygen, nitrogen, sulfur, and ashes. Consequently this provides reduced potential for the emissions of toxic and polluting gases, as well as in the corrosion rate. A higher calorific value due to a greater concentration of fixed carbon was also observed. Sjolie [195] specifies that emissions corresponding to one ton of charcoal vary from 1058 to 3027 kg of CO_2, which is lower than the emissions deriving from the combustion of gasoline, diesel, oil, and coal, being this a factor that contributes to increasing demand for biofuels.

According to the data published by the World Energy Outlook [196], for the national energy scenario in 2015, the expectation was generation of 15.1 Mtoe energy from mineral coal, while for biomass and solid waste the expectation was 70.6 Mtoe. By 2030, this is expected to be 18.0 and 89.8 Mtoe, respectively.

Bailis et al. [197], confirmed the data above, stating that biomass in the form of biofuels and sugarcane byproducts, accounts for the majority of the renewable energy used in the country, due to its favorable climate and geographical size. Large volumes of solid biomass (firewood) are used in industrial applications, while countries such as Asia and Africa use wood fuel to heat residential and commercial premises. Data published by the IEA [198] indicate that wood and sugarcane waste are the main raw materials used as solid biofuels in Brazil, because charcoal is predominantly employed by the steel mills in the state of Minas Gerais.

In order to increase the use and production of charcoal and biochar at national and international levels, Pereira et al. [199] indicate that some issues should be investigated in relation to the qualitative and quantitative assessment of the different types of furnaces used by the industries. This investigation should include a technical and economic analysis of the use of this equipment and of the technologies to be applied for the collection of condensable gases. Verification of the geographical distribution of the raw materials, the industries producing these fuels, and places of final use should also be evaluated to validate the feasibility of transport logistics. Moreover, the production systems, according to automation, process control, equipment maintenance, and product quality of each industry, should be compared when using this coal.

It is also required that government policies encourage production and consumption of renewable energy by provision of credit lines to fund the implementation of new technologies, and to improve existing production systems.

3. Final considerations

Among the main advantages of using solid biofuels, the continuous availability of large quantities of lignocellulosic biomass, their increased energy density, and low levels of greenhouse gas emissions produced during their combustion are worth mentioning.

These benefits have been generating great interest in expanding the use of solid biofuels, and this tendency is corroborated based on future expectations. This is because large amounts of agricultural and forestry waste has already been burned directly. Lignocellulosic biomass in its natural form, even with great potential and significant impact for the generation of energy in agro industries, due to its characteristic fibrous structure, granulometry, water content, and low energy density, does not have the ideal energy profile for direct combustion. It can however, be maximized by means of conversion technologies, such as gasification or charcoal production, by means of torrefaction and carbonization, and creation of pellets, briquettes, and chips.

Some technologies are more preferable than others, and maximizing the increasing use of solid biofuels depends on the type, specifications, and availability of biomass, development of industrial technologies, costs, and furnace adaptation. In addition, there are significant challenges regarding environmental legislation, policies of use, government incentives, and the competitiveness of solid biofuels compared to fossil fuels.

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